Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Sam Dolinar
Aaron Kiely
Matt Klimesh
Ryan Mukai
Shervin Shambayati

Jet Propulsion Laboratory

Antonio Ortega
Baltasar Beferull-Lozano*
Sang-Yong Lee**
Phoom Sagetong
Hua Xie

University of Southern California

* *now at Swiss Federal Inst. Of Tech.-EPFL*
** *now at Texas Instruments, Dallas, TX*

Roberto Manduchi
Ajoy Frank

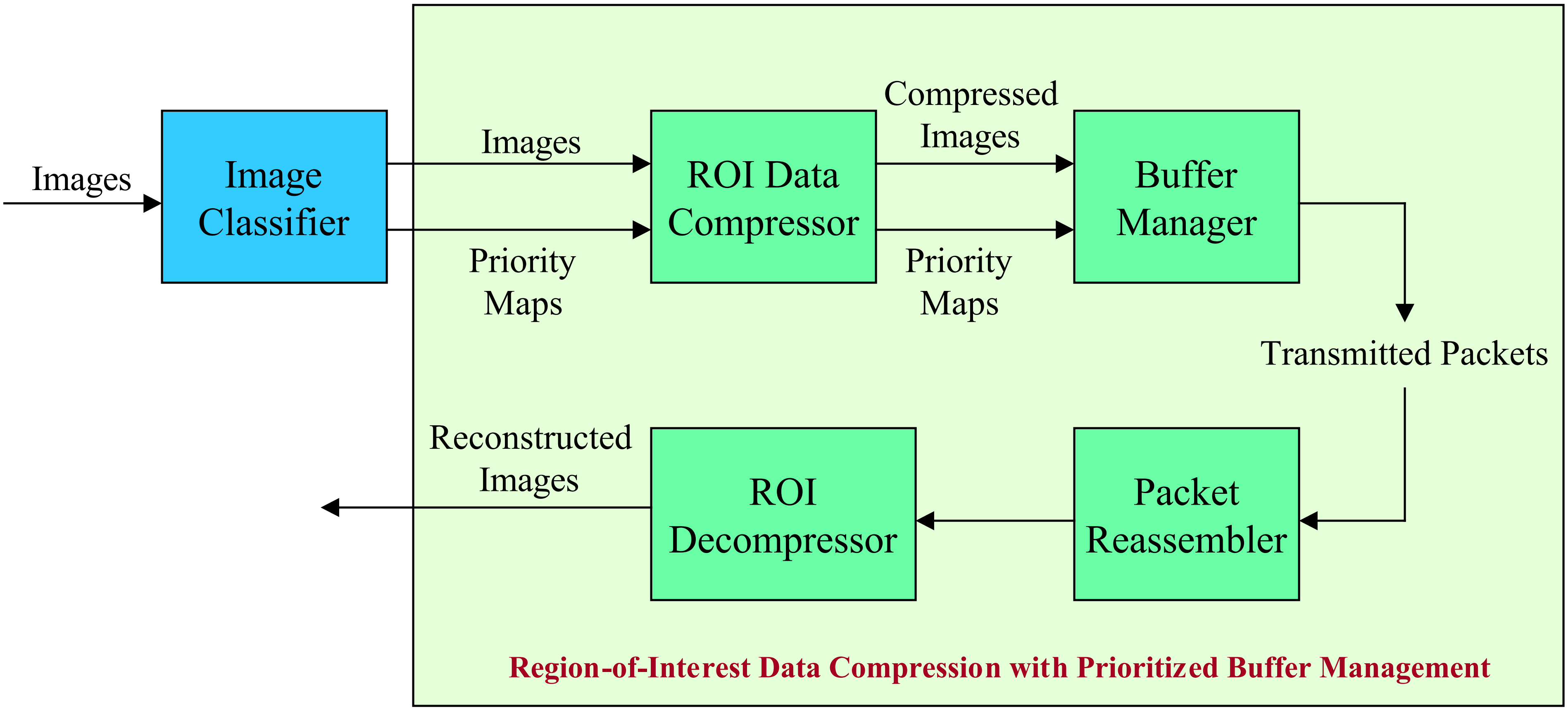
University of California, Santa Cruz

June, 2003

Part I:

Overview of Project

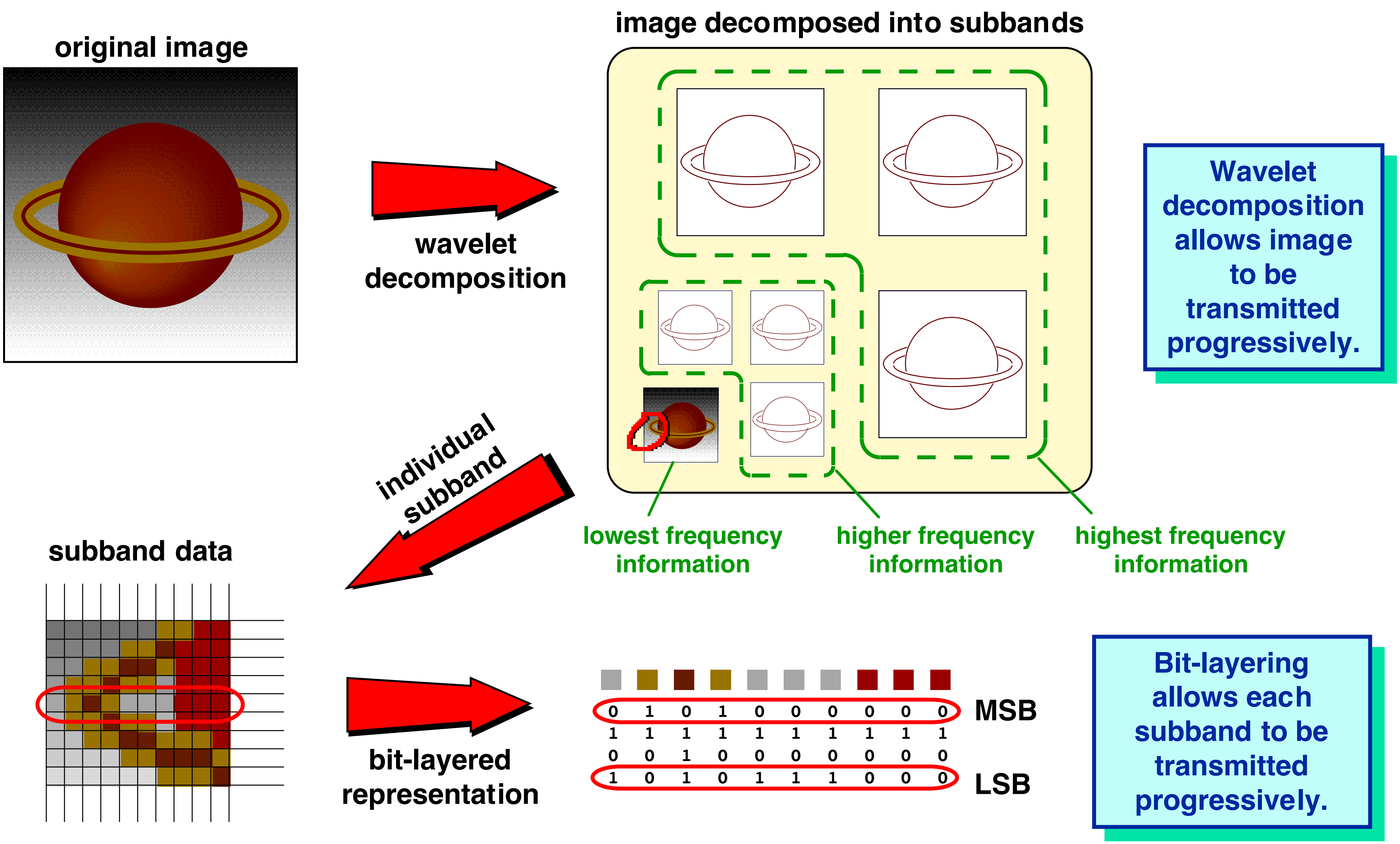
Block Diagram of the Onboard Processing System



Progressive Compression of Prioritized Data

- Image is transformed using a wavelet decomposition
  - Modification of ICER progressive compression used on Mars Exploration Rover (MER) just launched
- Priority map is computed for the transformed image to maintain spatial correspondence
  - Priorities are accommodated by left-shifting (scaling by 2) wavelet-transformed pixels according to their corresponding priorities
  - Output compressed data consists of successive bit planes of priority-scaled levels of wavelet decomposition
- Output data packets form a progressively coded "chain"
  - The full chain of packets would allow lossless (or essentially lossless) reconstruction of the corresponding sub-image
  - Truncation of the chain at any point yields a subset of packets useful for reconstruction
  - Amount of distortion depends on how many packets are truncated

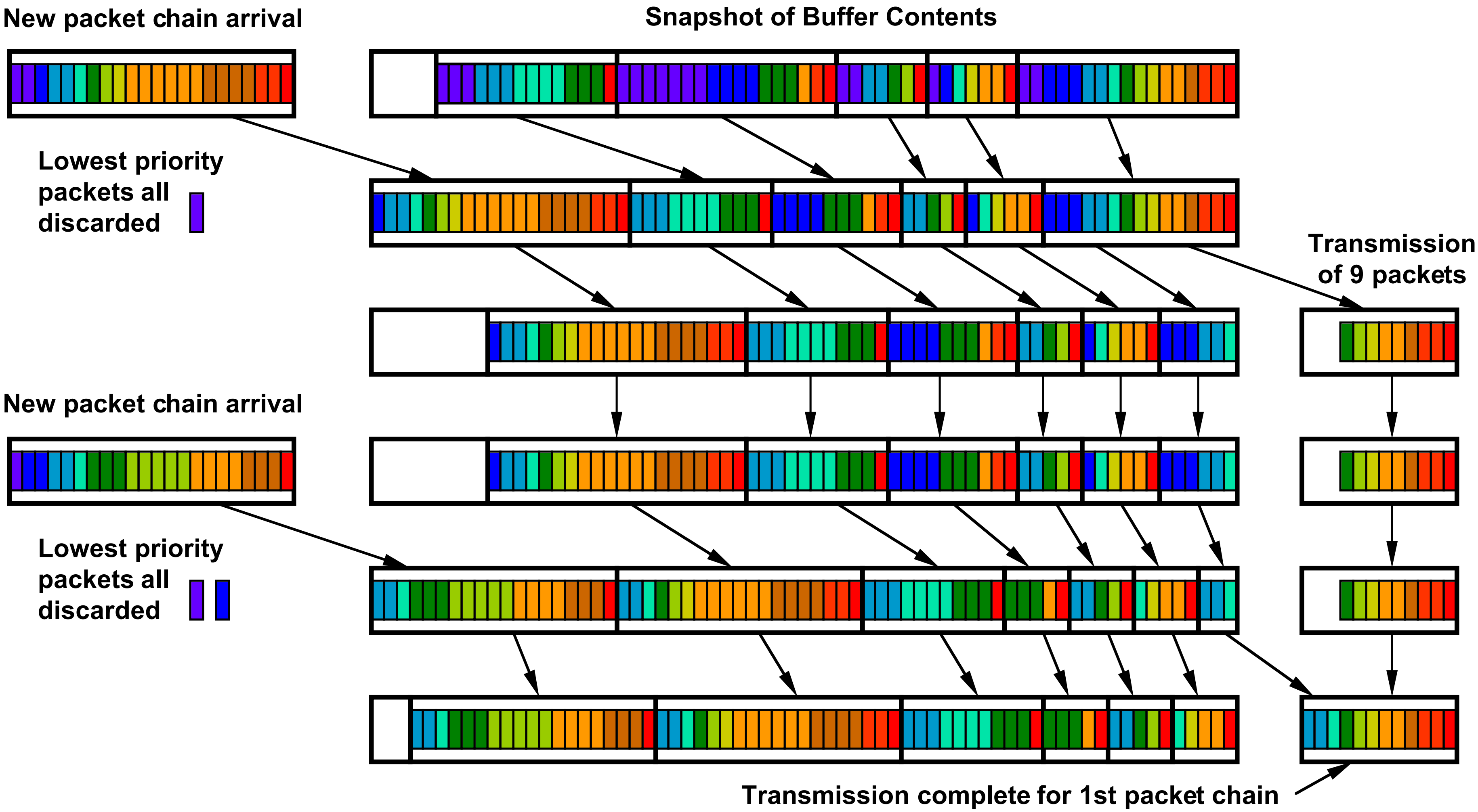
Progressive Compression using Wavelets



Goal at each stage: Transmit the compressed bit layer from the subband that gives the largest improvement in image quality per transmitted bit.

Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Buffer Manager's Admission and Transmission Protocols



Outline of Work in the 3rd Year

- Classification/prioritization algorithms for a specialized application to identify regions of interest from aerial images of wildfires
- New research into onboard feature detection and compression with distributed classification algorithms
  - Design of minimum-distortion Decision Tree Classifier with rate and complexity constraints
  - Application of Transform Coding with Linear Discriminant Analysis for more efficient classification performance
- Feature detection and compression using steerable transforms to achieve rotational invariance
- Development of a Web-accessible testbed site to allow remote users to test the functionality and utility of the region-of-interest data compression & prioritized buffer management (ROI-ICER & PBM) software

Part II:

Classification & Prioritization for Wildfire Application

Prioritization of Aerial Wildfire Images from UAV

- The Ecosystem and Technology Branch at NASA Ames (Branch Chief: Jim Brass) was enthusiastic about implementing the ROI-ICER & PBM software on a UAV-based wildfire management system
- In this application, an Unhabitated Aerial Vehicle (UAV) detects and monitors fire areas with multispectral airborne sensors
- The First Response Experiment (FiRE) (http://geo.arc.nasa.gov/sge/UAVFiRE) has shown that the available downlink transmission rate poses a serious bottleneck to real-time transfer of relevant information to wildfire managers and firefighting personnel

The FiRE System

- Current implementation:
  - Data collected by a 4-channel Airborne Infrared Disaster Assessment System (AIRDAS) instrument
  - Sensor was flown aboard the ALTUS II UAV for the FiRE experiment
  - Low-resolution video transmitted from an onboard video camera
    - Data acquisition start/stop time determined by ground-based human operator
  - Multispectral data compressed in JPEG
  - Over-the-horizon telemetry via INMARSAT satellites (64 kb/s)

The AIRDAS Instrument

- AIRDAS instrument collects images in four bands:
  - Band 1 (visible, 0.61–0.68 μm) suitable for monitoring smoke plumes as well as distinguishing cultural and vegetative not obscured by smoke or clouds.
  - Band 2 (1.57–1.70 μm) suitable for analysis of vegetative composition, as well as very hot fire fronts, while still penetrating most associated smoke plumes
    - Sensitive to fires and hot spots at temperatures above 573°K (300°C).
  - Band 3 (3.60–5.50μm) specifically designed for analysis of distinct fire temperatures while penetrating the associated smoke column.
  - Band 4 (5.50–13.0μm) designed to collect thermal data on earth ambient temperatures and on the lower temperature soil heating conditions behind fire fronts, as well as the minute temperature differences in pre-heating conditions.

The AIRDAS Instrument (cont.)

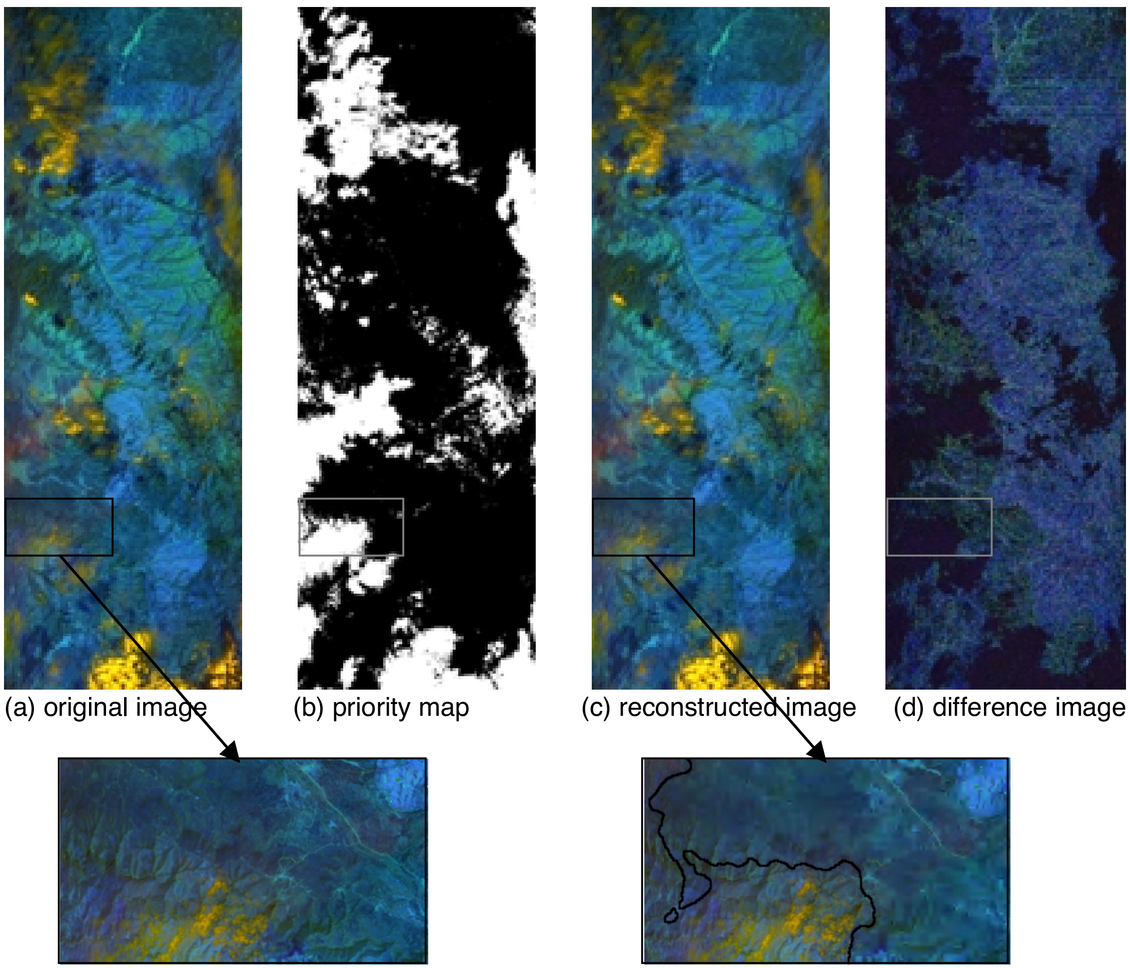
- Additional characteristics of the AIRDAS instrument:
  - Field of view: 108° cross-track
    - Instantaneous field of view of 2.62 milliradians.
  - 5-24 scans/second
  - Can operate in a flight envelope of 3,000 to 34,000 feet above ground, at aircraft ground speeds of 100 to 260 knots or greater
  - Digitized swath width of 720 pixels in the cross-track direction, with continuous data flow acquired in the along-track direction
    - Ground resolution of 8.0 meters at an aircraft altitude of 10,000 feet above ground
  - Raw data rate: 64,000 pixels/s (4 channels, 22 scans/s)

Priority Map Generation for This Application

- Highest priority:
  - Active fires, fire fronts and very hot surfaces
  - Can be identified by analyzing the ratio of radiance values in a long-wavelength and in a mid-wavelength band
- Also important:
  - Contextual neighboring portions
  - Landmarks such as roads and buildings
    - Should be preserved to facilitate geo-rectification
    - Can be detected based on line, edge and corner operators
- An automatic classification/prioritization algorithm incorporating both spectral band ratioing and contextual considerations was developed to produce priority maps for the aerial wildfire image application (see example on next slide)

Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Example of ROI-Prioritized Compression for Wildfire Aerial Imaging



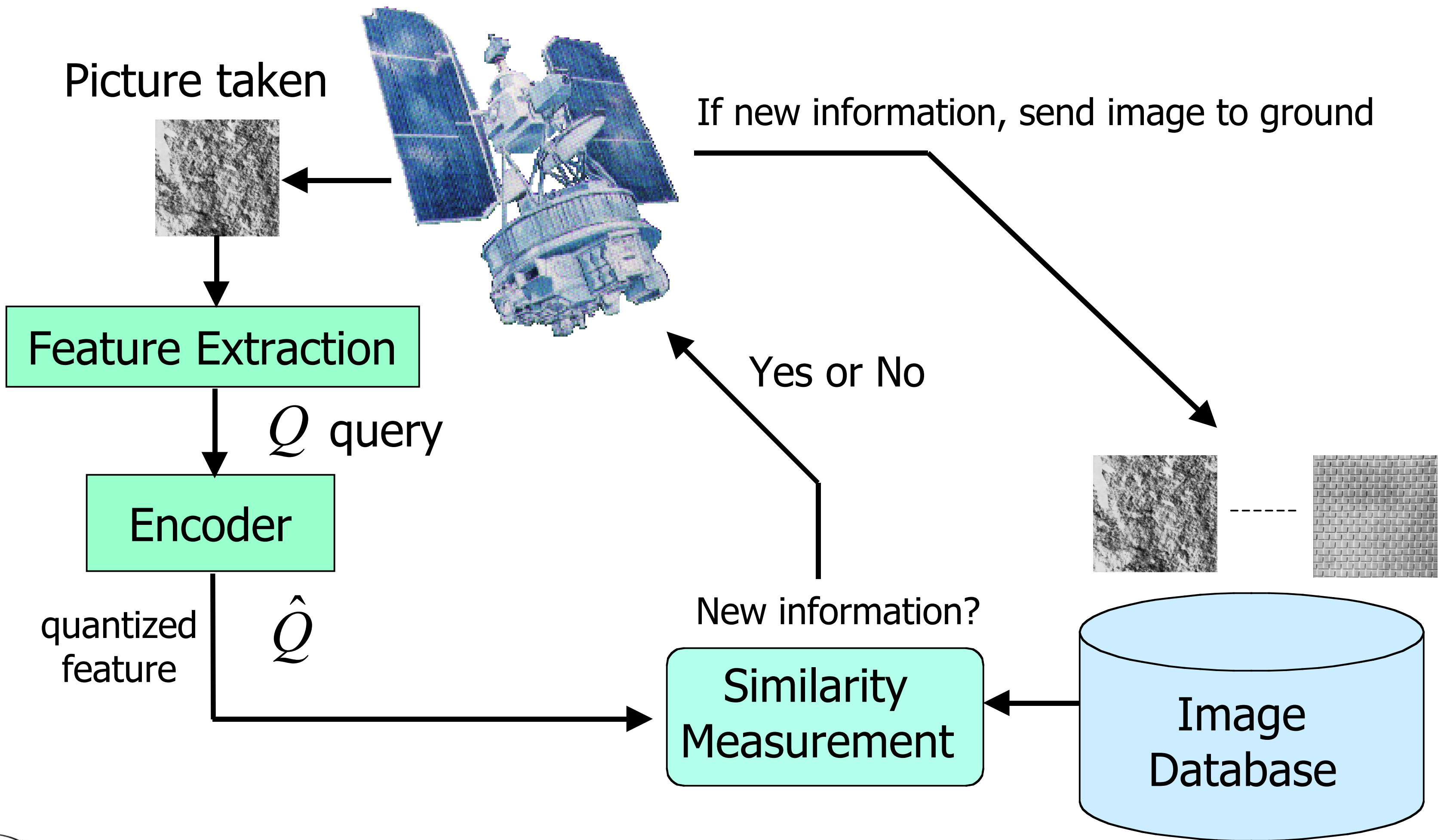
- **False-color images of July'02 Arizona wildfire using 3 bands (459 nm, 2.15 mm and 8.5 mm) from MAS multispectral imager**
  - **Original image (a) at 16 bits/pixel/band**
  - **Priority map (b) determined by band ratioing**
    - **white = highest priority**
  - **ROI-compressed image (c) at average rate of 0.68 bits/pixel)**
  - **Difference image (d) stretched by factor of 8 to highlight errors**
    - **dark = smallest errors**
- **Zoomed-in panels show effects of ROI-prioritized compression**
  - **Black curve is boundary between high- and low-priority regions**
  - **Differences in image quality across this boundary are evident in both the zoomed-in reconstructed image and the difference image**

Part III:

Distributed Feature Classification & Compression

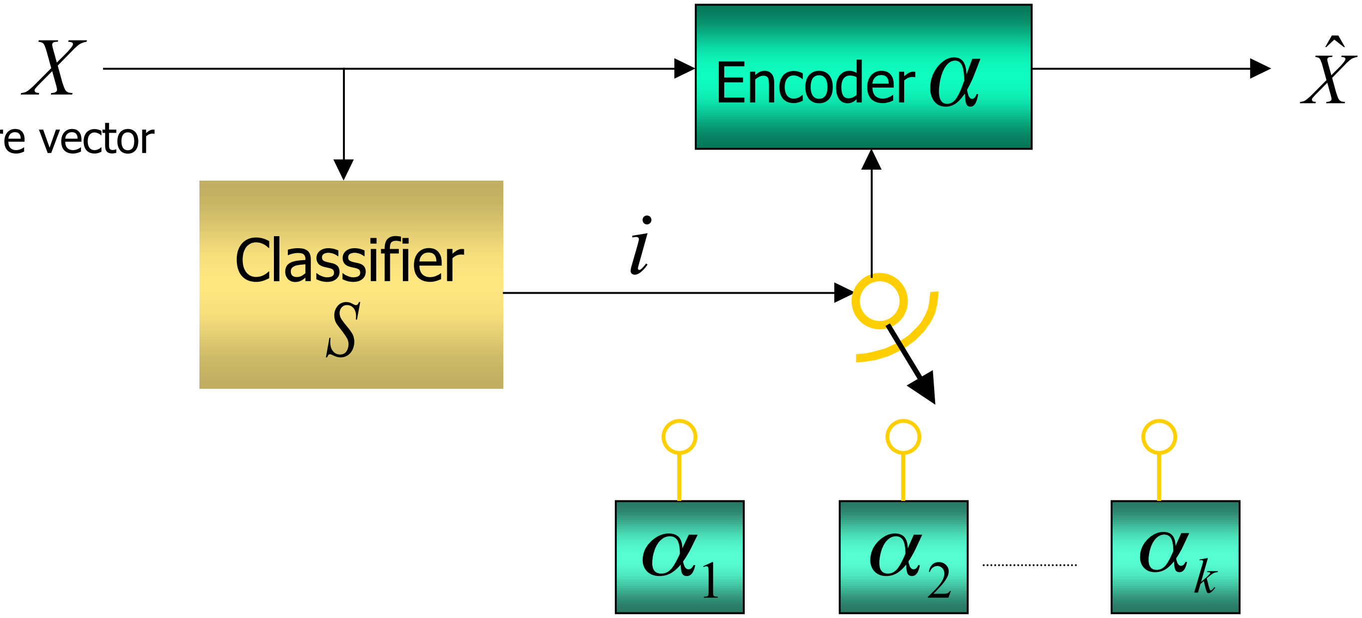
Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Feature Compression for Distributed Classification

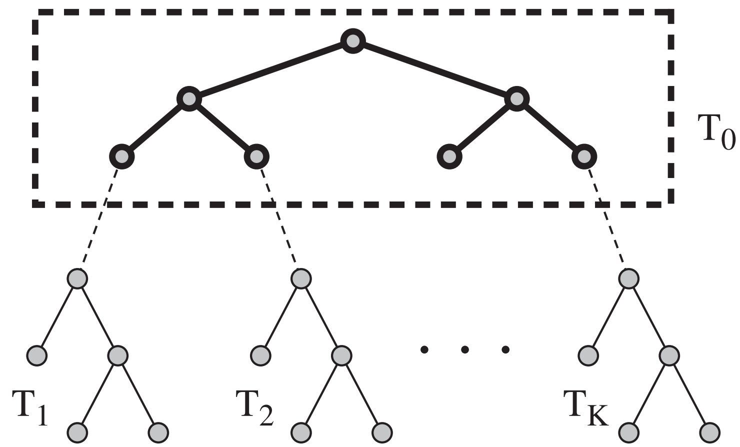


A Classified Encoding System

- Separate encoders $\{\alpha_i\}$ are designed for each class *i* to exploit the local statistics of the data
  - Each encoder α_i consists of uniform scalar quantizers for each vector component (stepsizes $\Delta_{i,j}$, $j = 1,\ldots,N$), followed by entropy coding (component by component)



Optimally Partitioning a Decision Tree Classifier



- Pre- and final classifications are performed using a decision tree classifier
  - Tree is partitioned into an onboard pre-classifier tree T_0 and subtrees $T_1,\ldots,T_K$ on the ground
  - Objective is to find an optimal pre-classifier T_0 to minimize a functional of misclassification risk, bit rate, and onboard computational load
    - Find optimal tradeoffs among distortion D, rate R, and complexity C
  - A generalized Breiman, Freidman, Olshen, Stone (G-BFOS) algorithm is used to jointly optimize the pruned subtree and the set of encoders

Region-of-Interest Data Compression with Prioritized Buffer Management (III)

- Use objective function with two Lagrange multipliers λ, μ

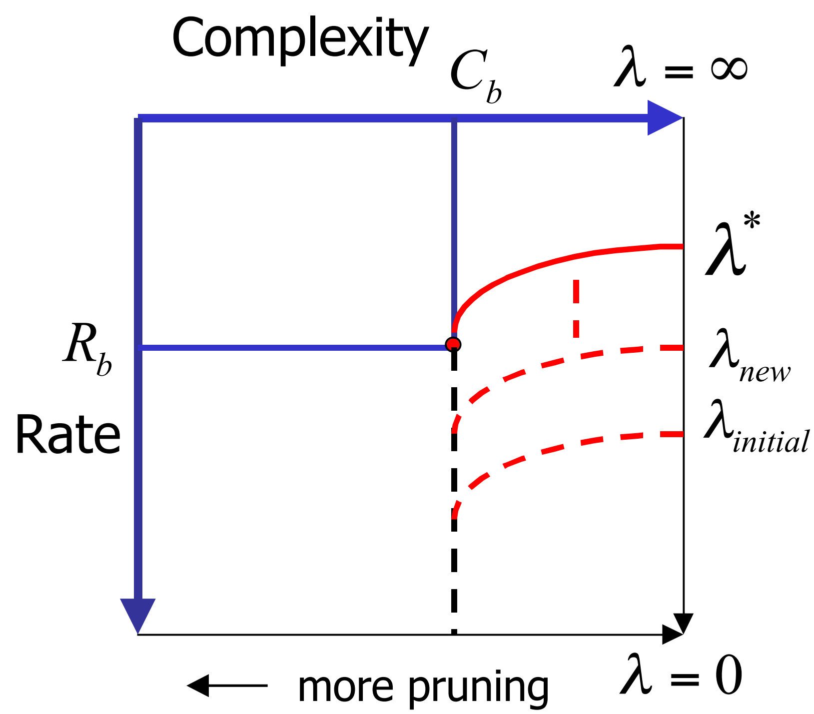
$$\min_{S \prec T, \{\Delta_{i,j}\}} \{D(S,\{\Delta_{i,j}\}) + \lambda \times R(S,\{\Delta_{i,j}\}) + \mu \times C(S)\}$$

- Global Optimality Theorem:

If $(S^*, \{\alpha_i^*\})$ is the solution of the unconstrained problem with multipliers λ and μ, then it is also the solution to the constrained problem for the particular case of $R_b = R(S^*, \{\alpha_i^*\})$ and $C_b = C(S^*, \{\alpha_i^*\})$

Illustrating the Constrained Optimization Method

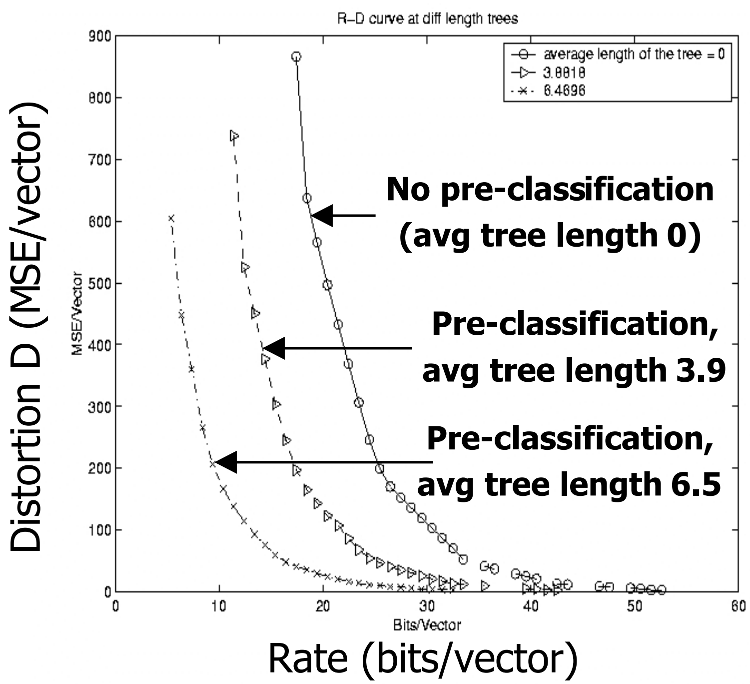
- Pruning using G-BFOS with fixed λ finds $(S^*, \{\alpha_i^*\})$ with complexity constraint satisfied, C_b
- Adjust λ using bisection to satisfy rate constraint, R_b

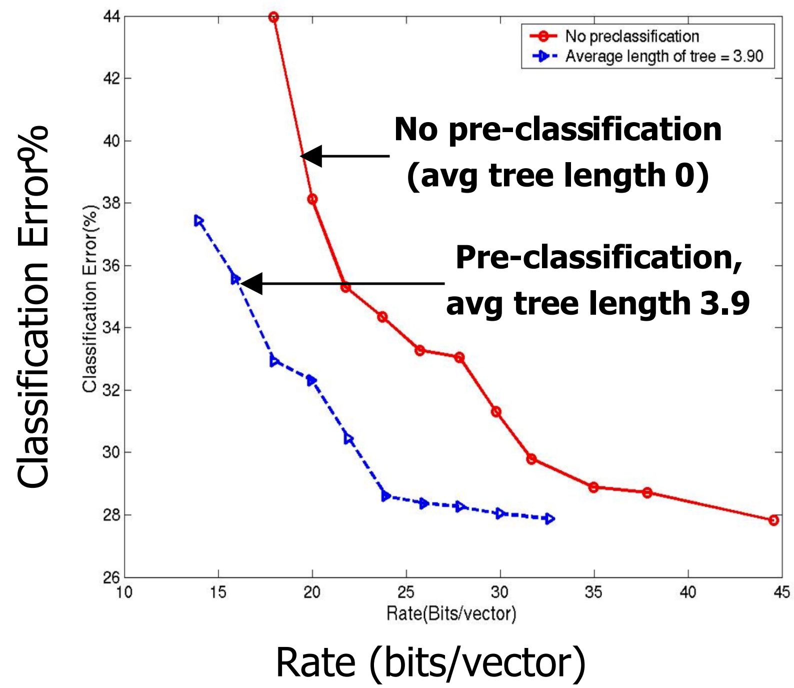


Performance Results

- Distortion (D) vs Rate (R) curves at constant complexity, with and without pre-classification

Classification Error% vs Rate (R), with and without pre-classification



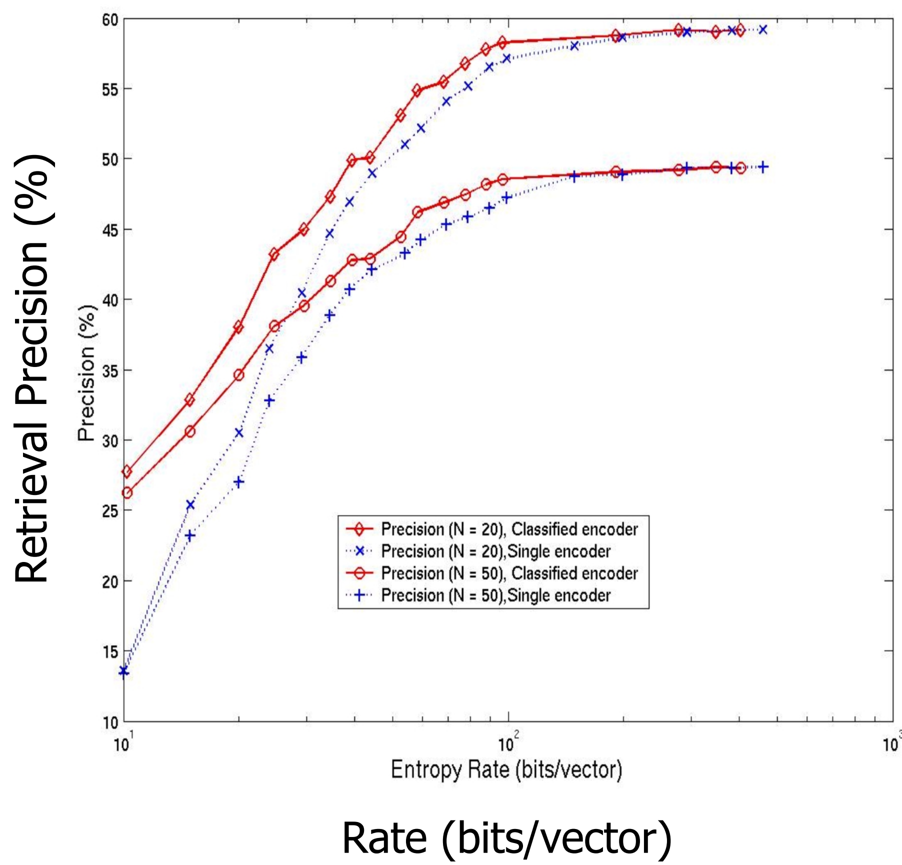


Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Performance Results on Corel Image Set

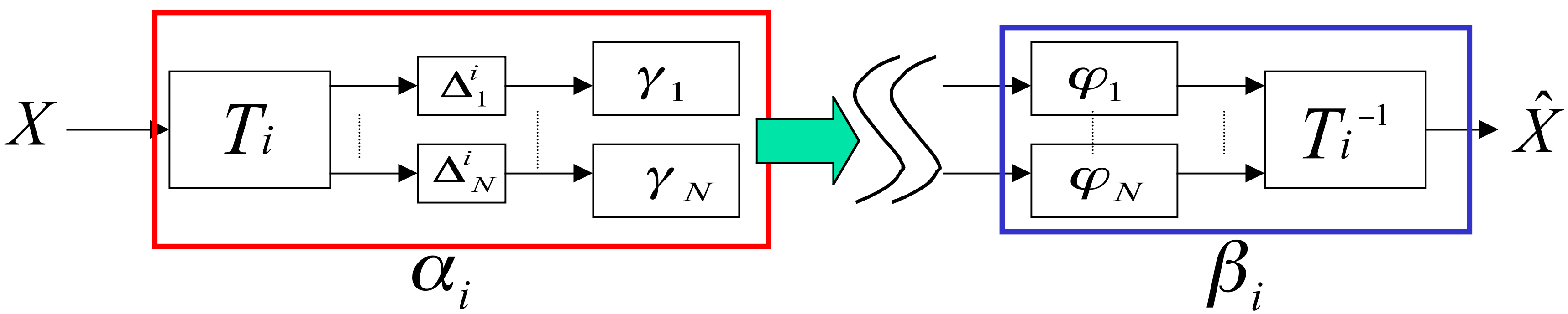
- Natural images
  - 15 image classes from Corel
    - Training: 80 of 100 images
    - Testing : 20 of 100 images
- Feature vectors (dim = 99)
  - Color histogram, texture histogram, edge histogram.
- Decision tree classifier
- 20-NN and 50-NN similarity searching
- Retrieval Precision =

$$\frac{\#\ \text{Retrieved Relevant Images}}{\#\ \text{Retrieved Images}}$$



Transform Coding and Linear Discriminant Analysis

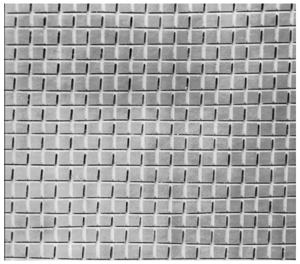
- Objectives
  - Design optimal quantizers for each class
  - Use more meaningful distortion measure than MSE
- Approach: Use transform coding and linear discriminant analysis
- A transform T_i and a set of stepsizes $\{\Delta^i_j, j = 1,\ldots,N\}$ are designed for each of the subspaces $i \in \{1,\ldots,k\}$



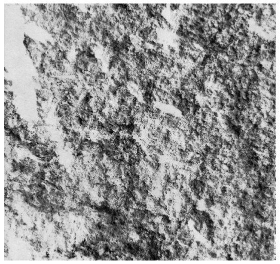
- Find the optimal transform T^* and stepsizes $\{\Delta^*_j, j = 1,\ldots,N\}$ to $\min_{T,\{\Delta_j\}} D(X,\hat{X})$ s.t $R \le R_{budget}$ and $C \le C_{budget}$

Linear Discriminant Analysis (LDA)

- Simple two-class example: discrimination is achieved through projection onto the eigenspace of the scatter matrix $S_w^{-1} S_b$

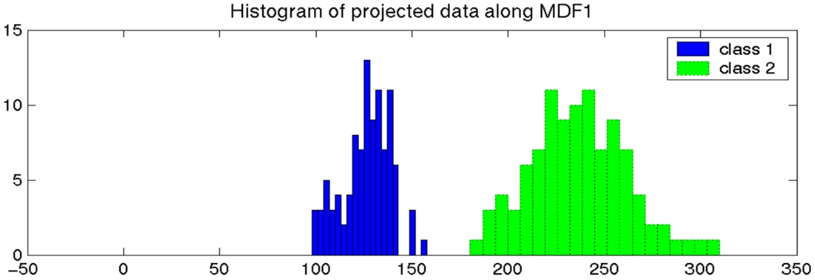


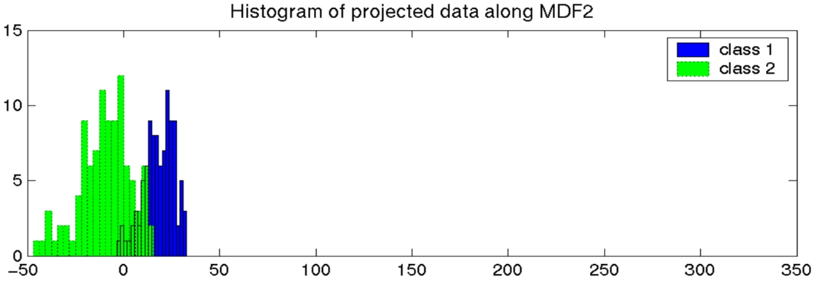
Class 1



Class 2

Histogram of projected data along eigenvector with larger eigenvalue



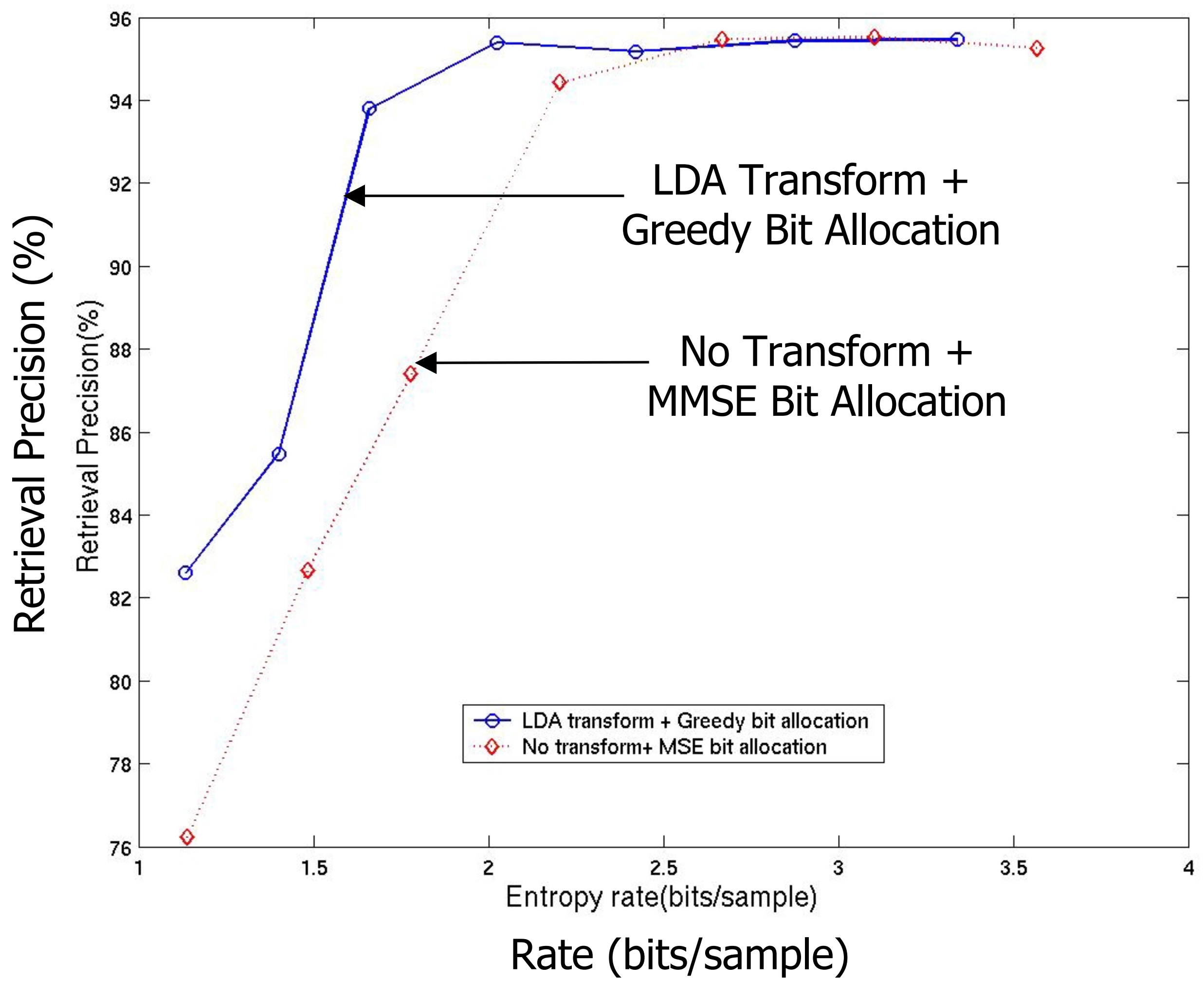


Histogram of projected data along eigenvector with smaller eigenvalue

- 2-dimensional wavelet features
- The two classes are well-separated after projection along eigenvector with larger eigenvalue

Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Performance of the LDA Transform Method

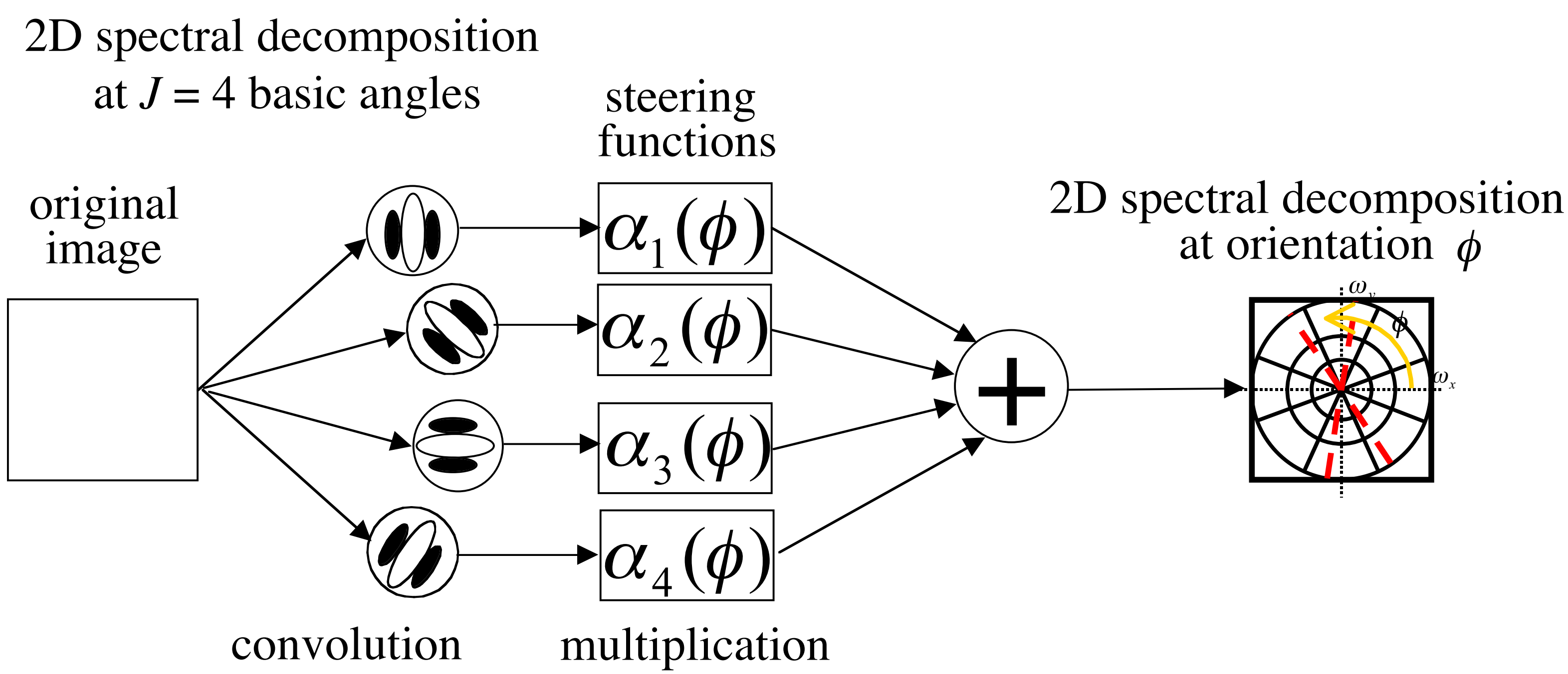


Part IV:

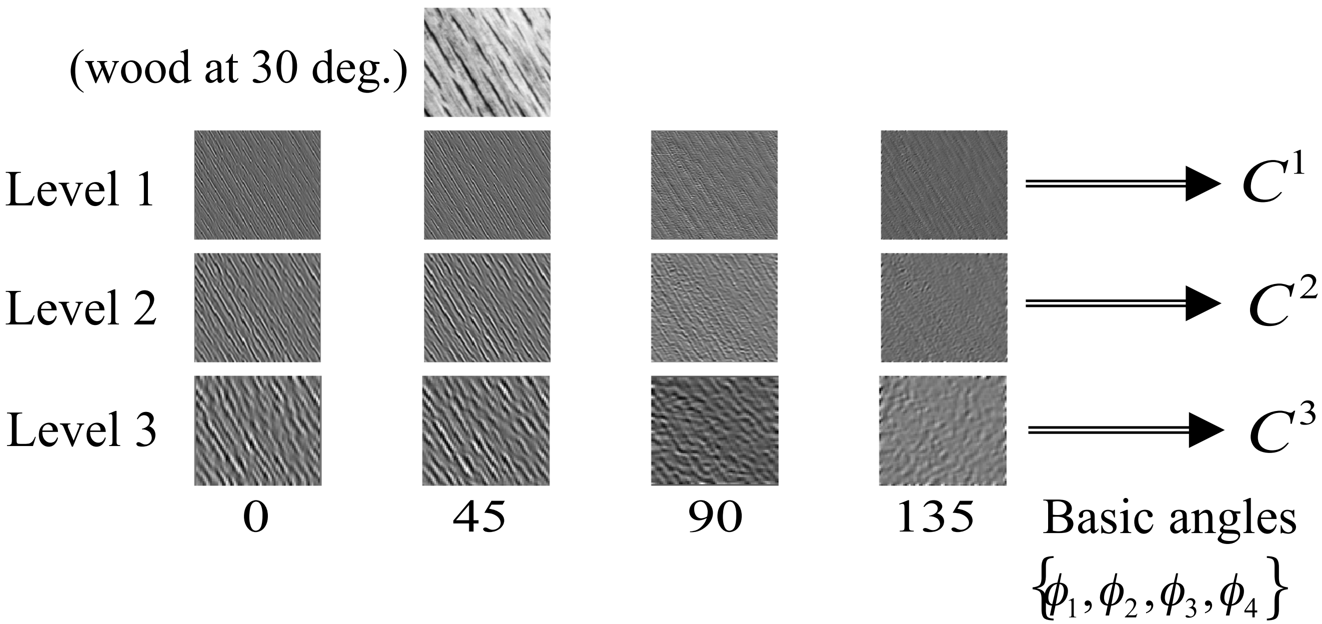
Rotationally Invariant Feature Extraction Using Steerable Transforms

Arbitrary Orientation Analysis of an Image

- Feature extraction is based on subbands from a steerable pyramid
- Steerable transforms are highly structured overcomplete transforms (Freeman, Adelson, Simoncelli, Perona, Manduchi, Teo)
- Arbitrary orientation filtering of an image is obtained by linear combination of outputs from a few fixed basic filters at a few discrete angles



Correlation Matrices as Texture Features



$$C^l = \begin{pmatrix} C_{11}^l & C_{12}^l & C_{13}^l & C_{14}^l \\ C_{21}^l & C_{22}^l & C_{23}^l & C_{24}^l \\ C_{31}^l & C_{32}^l & C_{33}^l & C_{34}^l \\ C_{41}^l & C_{42}^l & C_{43}^l & C_{44}^l \end{pmatrix}$$

= 4x4 correlation matrix for 4 basic angles at *l*-th level of steerable pyramid

Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Steerability of Features

If I_θ is image I rotated an angle θ $\left(\begin{array}{c}\text{counter}\\\text{clockwise}\end{array}\right)$

then $C^l_{I_\theta} = R(\theta) C^l_I R^T(\theta)\,, \qquad l = 1, \ldots, L$

where $$R(\theta) = \begin{pmatrix} \alpha_1(\phi_1-\theta) & \alpha_2(\phi_1-\theta) & \alpha_3(\phi_1-\theta) & \alpha_4(\phi_1-\theta) \\ \alpha_1(\phi_2-\theta) & \alpha_2(\phi_2-\theta) & \alpha_3(\phi_2-\theta) & \alpha_4(\phi_2-\theta) \\ \alpha_1(\phi_3-\theta) & \alpha_2(\phi_3-\theta) & \alpha_3(\phi_3-\theta) & \alpha_4(\phi_3-\theta) \\ \alpha_1(\phi_4-\theta) & \alpha_2(\phi_4-\theta) & \alpha_3(\phi_4-\theta) & \alpha_4(\phi_4-\theta) \end{pmatrix}$$

If $\{\phi_1, \phi_2, \phi_3, \phi_4\}$ equispaced $\Longrightarrow$ $R(\theta)$ is orthogonal

(Basic angles)

Rotationally Invariant Similarity Measurement

- Define a rotationally invariant distance between 2 images I_1 and I_2 :

$$D(I_1, I_2) = \underset{\theta}{\text{Min}} \left(\sum_{l=1}^{L} \left\| C_{I_1}^l - R(-\theta) C_{I_2}^l R^T(-\theta) \right\|_F \right)$$

- This D() enforces the same rotation angle θ across all levels *l* of the pyramid

- Decision Tree Classifier with Alignment:
  - Define distance of query Q to node t

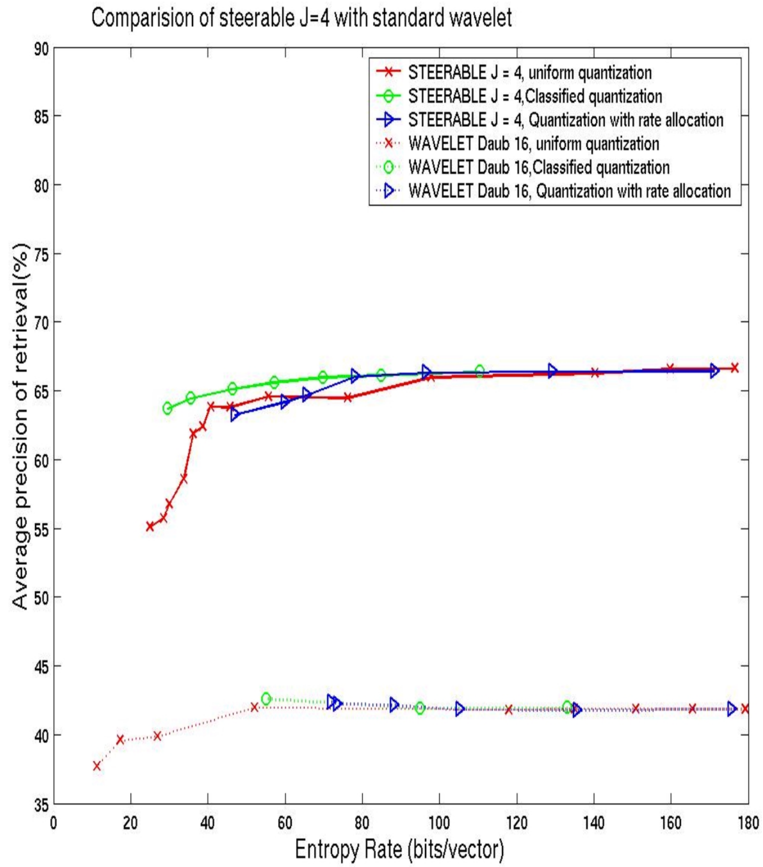
$$\underline{D}(Q,t) = \min_{\theta} D(Q_\theta, I_c) - R(t)$$

where *R*(*t*) is radius (from centroid) of node *t*

  - Finds best alignment at each node of tree
  - True closest match is found at each node

Retrieval Precision Using Compressed Features

- Training:
  - 13 non-rotated Brodatz textures
- Testing:
  - Rotated textures at : 30, 60, 90 and 120 degrees
- 3 Feature Compression methods:
  - Simple uniform quantization
  - Non-uniform quantization with bit allocation
  - Decision tree classifier with quantization
- Steerable transform beats wavelet transform in retrieval precision (65% vs 40% at high bit rate)
- Classified quantizer rises to asymptotic precision level at lower bit rates



Part V:

The Web-Accessible Testbed

The Web-Accessible Software Testbed

The web-accessible testbed will be the primary means of demonstrating system capabilities to scientists with diverse earth-science applications

- **Testbed functionality and requirements**
  - **Flexibility for scientists to define the test scenarios**
    - **Accept sets of test images from scientists or from a built-in library**
    - **Generate random or deterministic order of arrival, and random or deterministic arrival rates**
    - **Allow scientists to draw regions of interest by hand**
  - **Flexibility for scientists to update run-time parameters**
    - **Allow scientist to change the number of prioritization levels and prioritization values. Also, prioritization values should be changeable "online" as the simulation is running.**
    - **When automatic prioritization is implemented, allow scientists to change algorithm parameters. For example, if "vegetation indices" (spectral ratios) are used for classifying different regions, the testbed should allow scientists to change the coefficients involved.**
  - **Show baseline scenarios for comparison**
    - **Uniformly compress all images to meet a downlink constraint**
    - **Randomly select images to be transmitted to meet given quality level (and discard the rest)**
    - **Allow scientists to hand-pick transmitted images to fit the downlink constraint (as an optimistic benchmark)**
  - **Provide scientists with reconstructed images for evaluation relative to originals**

Current Status of the Web-Accessible Software Testbed

- Beta version of web site is up and running
  - Allows remote user to run full end-to-end simulations of the region-of-interest compression and prioritized buffer management software (ROI-ICER & PBM)
  - URL is http://gallager.jpl.nasa.gov/welcome.html
- Accessibility of Web site
  - From a JPL computer
  - To project participants from a non-JPL computer
  - To external scientists by request

User Inputs to the ROI-ICER & PBM Simulation

- User specifies simulation parameters
  - Image arrival rate and transmission rate
  - Buffer size
- User selects a sequence of images to test, from either:
  - A built-in database of images and priority maps
  - A user-uploaded set of images and priority maps or classification maps
    - A user-specified table can alter the mapping from classes to priorities, or stretch/squeeze the range of priorities

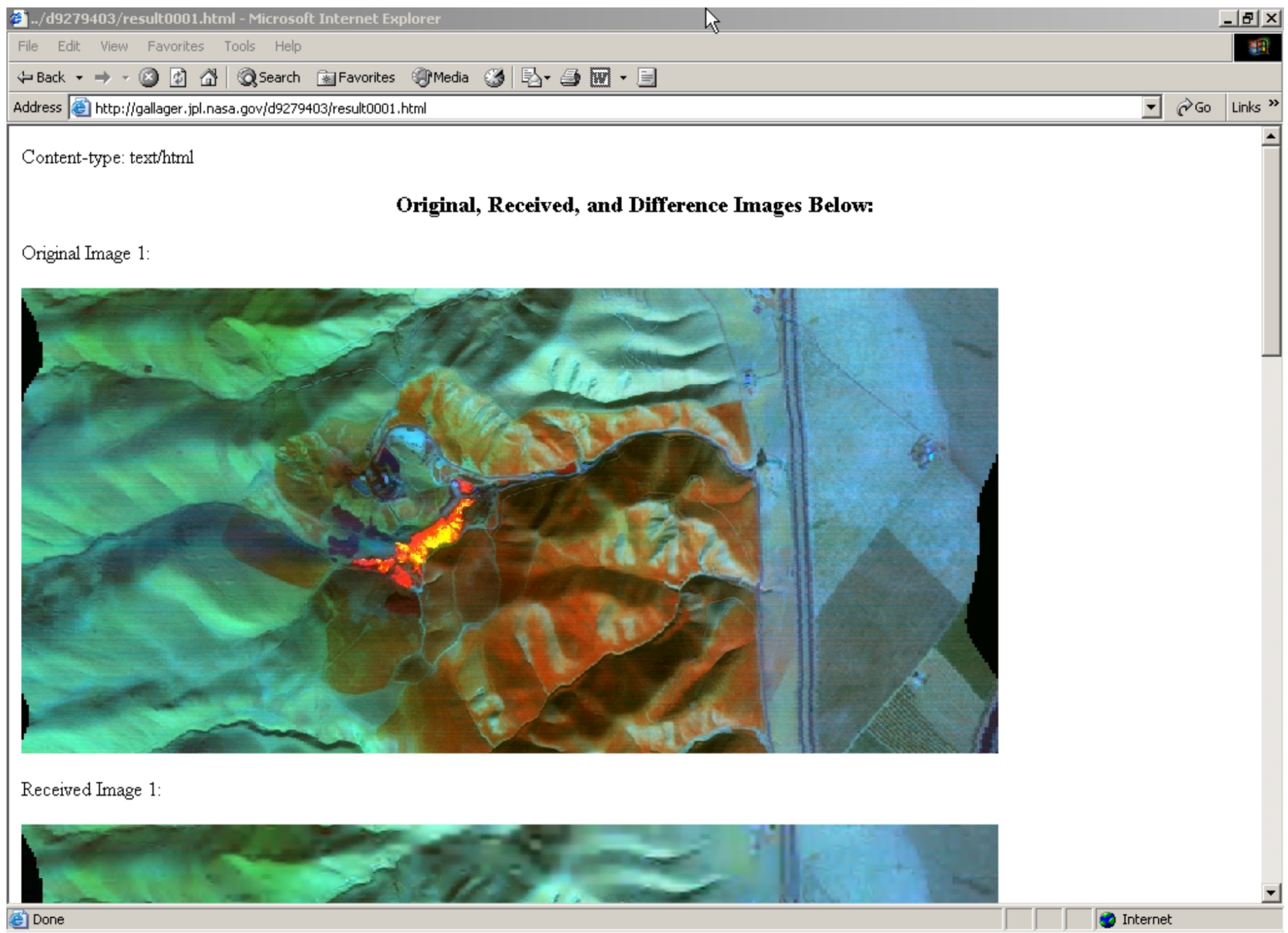
Simulation Results Reported to the User

- A page for each individual image displays the original, received, and difference images, and the priority map
- The user has links to download all four files in PPM format
  - Allows scientist to evaluate raw reconstructed image according to any desired user-pertinent criteria off-line
- Each individual image page shows simulation statistics and performance measures for that image

Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Screen Snapshot of Individual Image Page

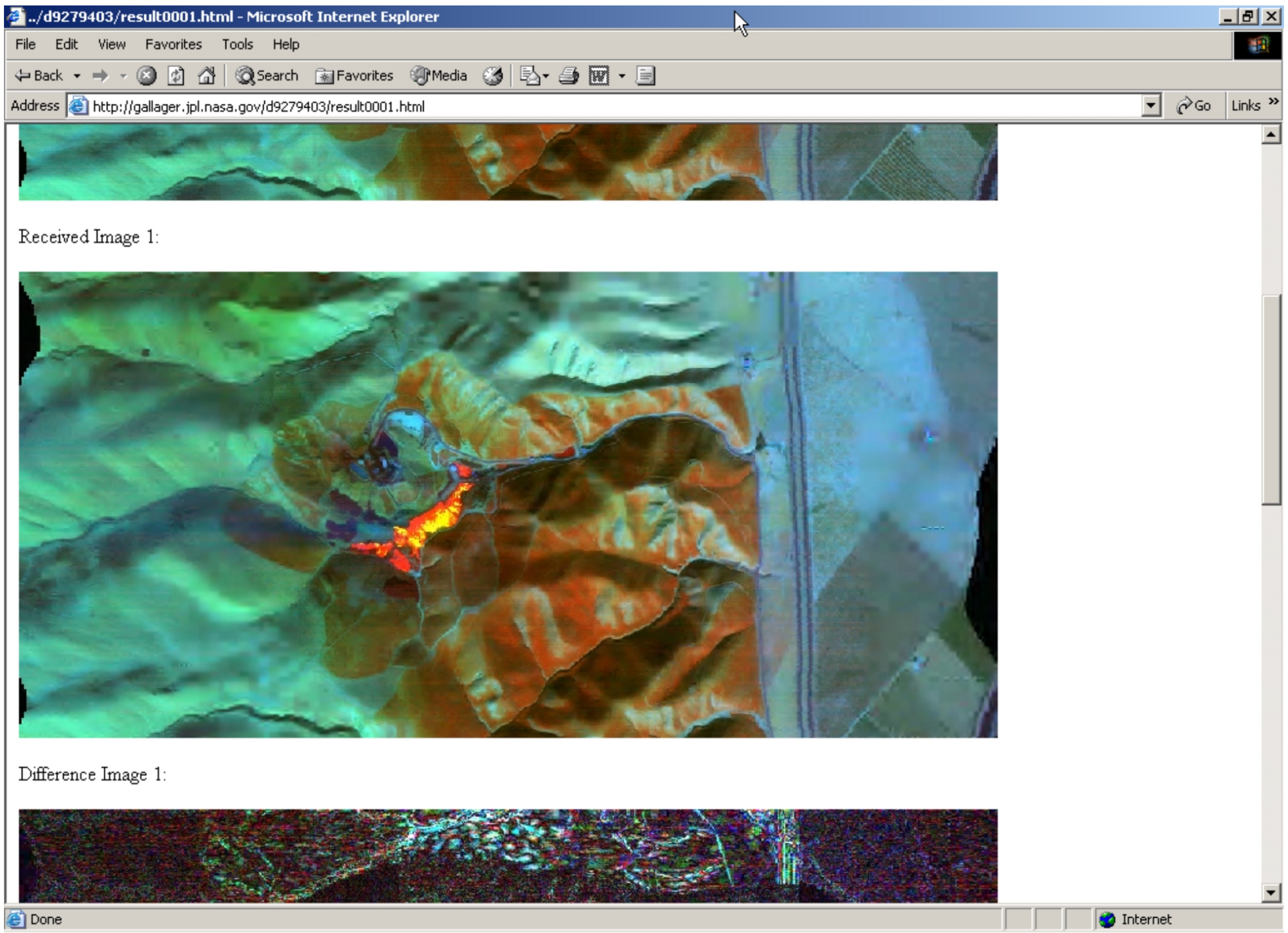
Original Image



Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Screen Snapshot of Individual Image Page (scrolled)

Reconstructed Image →

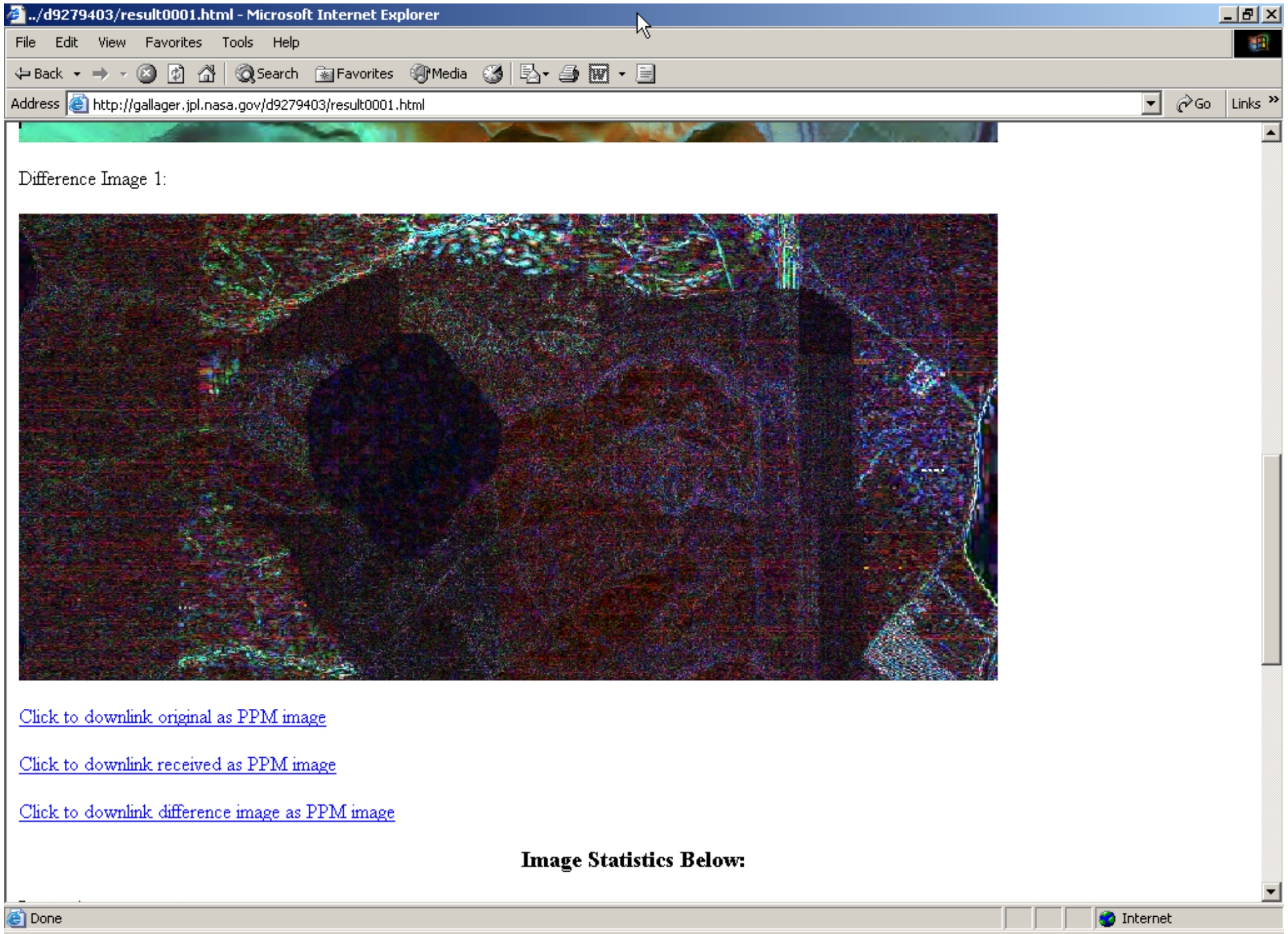


Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Screen Snapshot of Individual Image Page (scrolled more)

Difference Image →

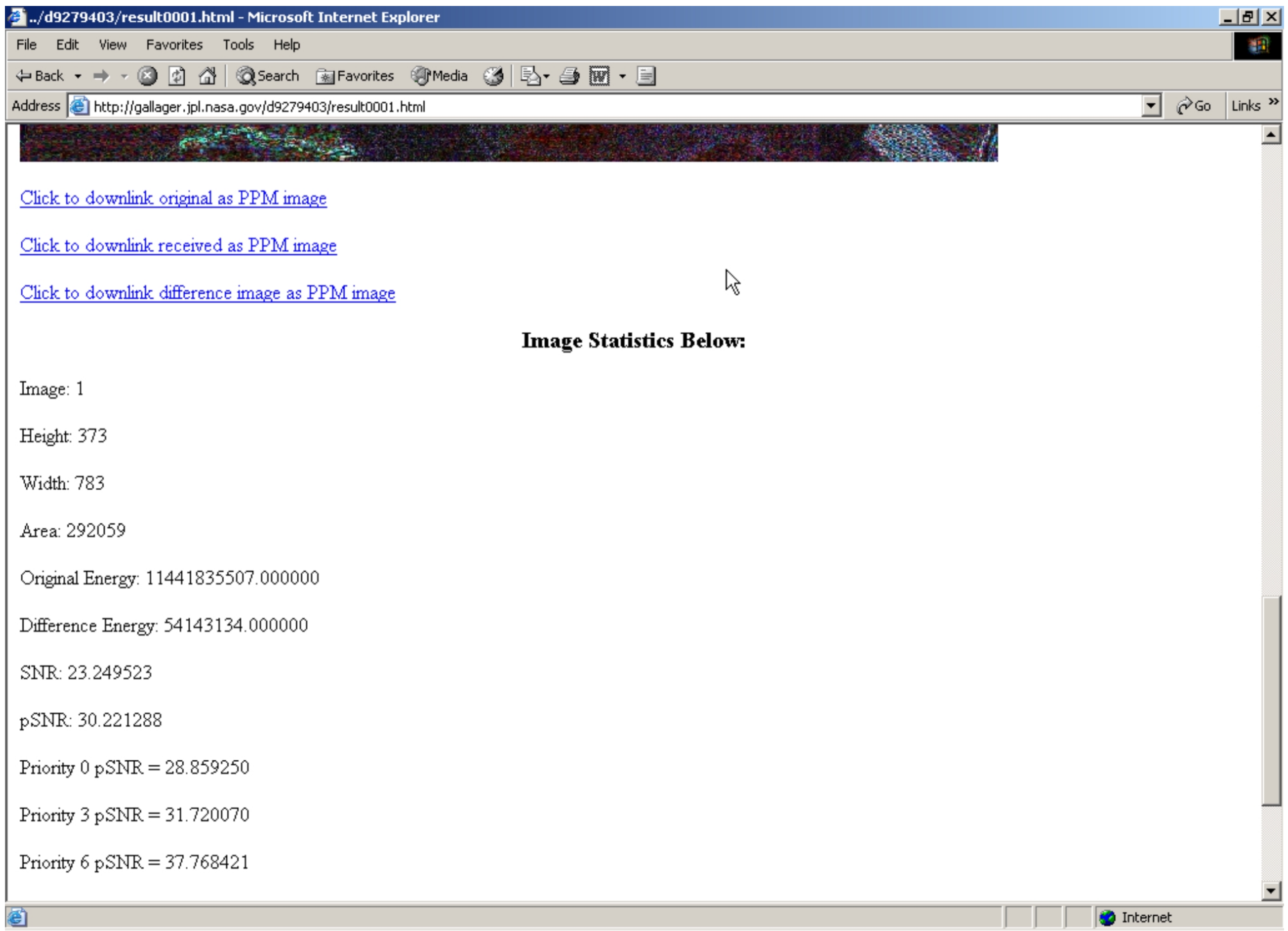
Priority Map (to be added) →



Screen Snapshot of Individual Image Page (scrolled more)

Download Raw Data →

Image Statistics & Performance Measures →



Region-of-Interest Data Compression with Prioritized Buffer Management (III)

Screen Snapshot of Individual Image Page (scrolled more)

(More) Image Statistics & Performance Measures →